

The First Detailed Abundances for M giants in the inner Bulge from Infrared Spectroscopy

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ABSTRACT

We report the first abundance analysis of 17 M giant stars in the inner Galactic bulge at $(l, b) = (0^\circ, -1^\circ)$, based on $R = 25,000$ infrared spectroscopy ($1.5 - 1.8 \mu\text{m}$) using NIRSPEC at the Keck telescope. Based on their luminosities and radial velocities, we identify these stars with a stellar population older than 1 Gyr. We find the iron abundance $\langle [\text{Fe}/\text{H}] \rangle = -0.22 \pm 0.03$, with a 1σ dispersion of 0.14 ± 0.024 . We also find the bulge stars have enhanced $[\alpha/\text{Fe}]$ abundance ratio at the level of $+0.3$ dex relative to the Solar stars, and low $<^{12}\text{C}/^{13}\text{C}> \approx 6.5 \pm 0.3$. The derived iron abundance and composition for this inner bulge sample is indistinguishable from that of a sample of M giants our team has previously studied in Baade’s Window $(l, b) = (0.9, -4)$. We find no evidence of any major iron abundance or abundance ratio gradient between this inner field and Baade’s window.

Subject headings: Galaxy: bulge — Galaxy: abundances — stars: abundances — stars: late-type — techniques: spectroscopic — infrared: stars

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1. Introduction

High resolution infrared (IR) spectroscopy now enables the possibility of undertaking abundance analysis for cool late-type giants. The technique is especially powerful in extending abundance studies to regions of high extinction, such as the inner disk and bulge. We have reported the first detailed abundances for Galactic bulge M giants (Rich & Origlia 2005) in Baade’s Window, a field with low enough extinction that optical high resolution spectroscopy is also feasible (McWilliam & Rich 1994; Fulbright, McWilliam & Rich 2006, 2007; Zoccali et al. 2006). Our IR spectroscopy has been in basically good agreement with these optical studies, finding roughly Solar mean abundance and enhanced alpha elements, consistent with a predominant chemical enrichment by type II SNe on a relatively short timescale (Matteucci, Romano & Molaro 1999; Ballero et al. 2007).

Here we exploit these techniques to push into the high extinction regions of the inner Galactic bulge, where optical spectroscopy is impossible. Our goal is to constrain whether an abundance or abundance ratio gradient is present in the bulge population. The Galactic Center contains old stars (e.g. Figer et al. 2004) and the bulge in Baade’s Window and other fields has been demonstrated to be globular cluster age (Ortolani et al. 1995; Kuijken & Rich 2002; Zoccali et al. 2003). Our aim has been to select the *old* red giant stars that lies near the red giant branch (RGB) tip a factor of four closer to the nucleus than the well studied Baade’s window field, at $(l, b) = (0^\circ, -1^\circ)$, i.e. only ≈ 140 pc distant from the nucleus (adopting $R_0 = 8$ kpc), with the goal of measuring possible abundance gradients in the inner Galactic bulge.

At present, there is no secure measurement of the bulge abundance gradient. Frogel et al. (1999) used broadband JK photometry to probe fields along the major and minor axis from $-4^\circ < l, b < 0^\circ$, reaching within 0.2° of the Galactic Center. This study, which found no indication of a significant gradient, provided the input sample for Ramírez et al. (2000), who also found no gradient using low resolution measurements of Ca, Na, and CO features in the $2\mu\text{m}$ window. The Ramírez et al. (2000) abundances were derived from a globular cluster-based calibration and consequently their abundances for $[\text{Fe}/\text{H}] > 0$ are an extrapolation; however, that was unlikely to have altered their findings. More recently, Zoccali et al. (2003) find a photometric abundance distribution at $(l, b) = (0.3^\circ, -6.2^\circ)$ very similar to that of Fulbright, McWilliam & Rich (2006) in Baade’s window. Viera et al. (2006) finds the same photometric abundance distribution in a proper motion selected sample of K giants in the Plaut field, at $b = -8^\circ$. These studies suggest that the bulge does not have a measurable abundance gradient over its inner kpc, but they all rely on photometric abundance constraints (RGB color) rather than on spectroscopy.

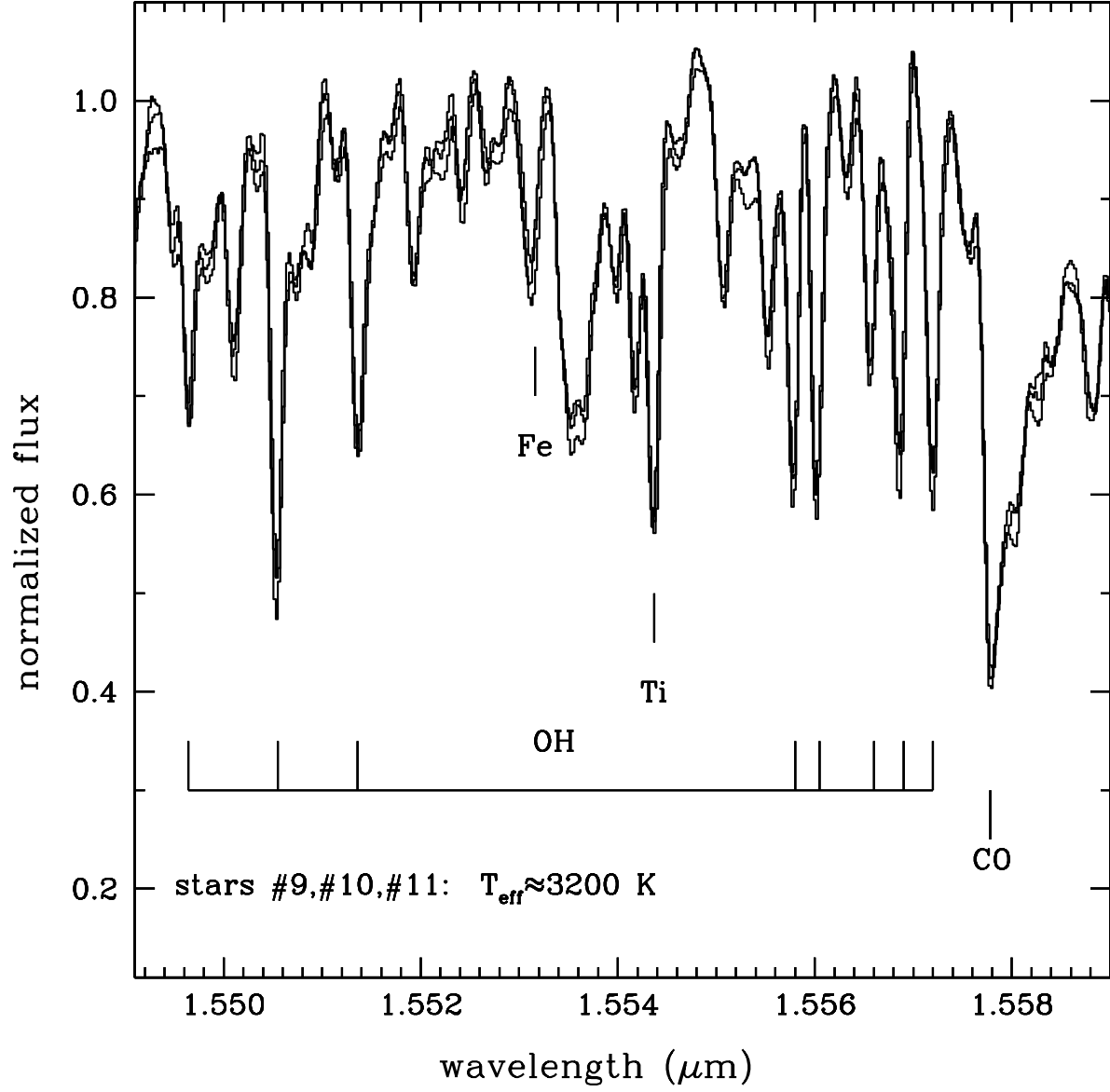


Fig. 1.— NIRSPEC H-band spectrum showing the region near $1.555 \mu\text{m}$ of three (#9, #10 and #11) of the coolest and more metal rich stars in our sample. A few major atomic lines and molecular bands of interest are flagged.

2. Observations and abundance analysis

A sample of M giants near the RGB tip in the inner Bulge field at $(l, b) = (0^\circ, -1^\circ)$ has been selected from the 2MASS K, J-K color magnitude diagram, corrected for reddening by using the interstellar extinction maps of Schultheis et al. (1999). Spectra for 17 stars with bolometric magnitudes $M_{\text{bol}} \geq -4$ were taken during 3 observing runs on April 2005, May 2005 and May 2006, by using NIRSPEC (McLean et al. 1998) at Keck II. A slit width of $0''.43$ giving an overall spectral resolution $R=25,000$, and the standard NIRSPEC-5 setting, which covers most of the 1.5-1.8 μm H-band have been selected.

The raw stellar spectra have been reduced using the REDSPEC IDL-based package written at the UCLA IR Laboratory. Each order has been sky subtracted by using nodding pairs and flat-field corrected. Wavelength calibration has been performed using arc lamps and a second order polynomial solution, while telluric features have been removed by using a O-star featureless spectrum. The signal to noise ratio of the final spectra is ≥ 30 . Fig. 1 shows an example of the observed spectra for 3 among the coolest and most metal rich giants in our sample.

A grid of suitable synthetic spectra of giant stars has been computed by varying the photospheric parameters and the element abundances, using an updated version of the code described in Origlia, Moorwood & Oliva (1993). By combining full spectral synthesis analysis with equivalent widths measurements of selected lines, we derive abundances for Fe C, O and other alpha-elements (Mg, Si, Ca and Ti). The lines and analysis method are described in Origlia, Rich & Castro (2002); Origlia & Rich (2004) and subjected to rigorous tests in our previous studies of Galactic bulge field and cluster giants (see Origlia & Rich 2004; Rich & Origlia 2005, and references therein). Reference solar abundances are from Grevesse & Sauval (1998).

In the first iteration, we estimate stellar temperature from the $(J - K)_0$ colors (see Table 1) by using an average reddening of $E(B-V)=2.9$ (Schultheis et al. 1999) and the color-temperature transformation of Montegriffo et al. (1998) specifically calibrated on globular cluster giants. Gravity has been estimated from theoretical evolutionary tracks, according to the location of the stars on the Red Giant Branch (RGB) (see Origlia et al. 1997, and references therein for a more detailed discussion). An average value $\xi=2.0$ km/s has been adopted for the microturbulence (see also Origlia et al. 1997). More stringent constraints on the stellar parameters are obtained by the simultaneous spectral fitting of the several CO and OH molecular bands, which are very sensitive to temperature, gravity and microturbulence variations (see Figs. 6,7 of Origlia, Rich & Castro (2002)).

CO and OH in particular, are extremely sensitive to T_{eff} in the range 3500 to 4500

K. Indeed, temperature sets the fraction of molecular *versus* atomic carbon and oxygen. At temperatures ≥ 4500 K molecules barely survive; most of the carbon and oxygen are in atomic form and the CO and OH spectral features become very weak. On the contrary, at temperatures ≤ 3500 K most of the carbon and oxygen are in molecular form, drastically reducing the dependence of the CO and OH band strengths and equivalent widths on the temperature itself (Origlia et al. 1997).

The final values of our best-fit abundances together with random errors are listed in Table 1.

As a further check on the statistical significance of our best-fit solution, we also compute synthetic spectra with $\Delta T_{\text{eff}} = \pm 200$ K, $\Delta \log g = \pm 0.5$ dex and $\Delta \xi = \mp 0.5$ km s $^{-1}$, and with corresponding simultaneous variations of the C and O abundances (on average, ± 0.2 dex) to reproduce the depth of the molecular features. As a figure of merit of the statistical test, we adopt the difference between the model and the observed spectrum (hereafter δ). In order to quantify systematic discrepancies, this parameter is more powerful than the classical χ^2 test, which is instead equally sensitive to *random* and *systematic* scatters (see also Origlia et al. 2003; Origlia & Rich 2004). Our best fit solutions always show $>90\%$ probability to be representative of the observed spectra, while those with ± 0.1 dex are significant at $\geq 1 \sigma$ level. Spectral fitting solutions with abundance variations of ± 0.2 dex, due to possible systematic uncertainties of ± 200 K in temperature, ± 0.5 dex in gravity or ∓ 0.5 km/s in microturbulence have $<30\%$ probability of being statistically significant. Hence, as a conservative estimate of the systematic error in the derived best-fit abundances, due to the residual uncertainty in the adopted stellar parameters, one can assume a value of $\leq \pm 0.1$ dex. However, it must be noted that since the stellar features under consideration show a similar trend with variations in the stellar parameters, although with different sensitivities, *relative* abundances are less dependent on the adopted stellar parameters (i.e. on the systematic errors) and their values are well constrained down to $\approx \pm 0.1$ dex (see also Table 1).

3. Results and Discussion

For the observed M giants we measure average $\langle [\text{Fe}/\text{H}] \rangle = -0.22 \pm 0.03$ and dispersion $1\sigma = 0.140 \pm 0.024$. This $[\text{Fe}/\text{H}]$ abundance distribution is very similar to the one measured in the Baade’s window (Rich & Origlia 2005), with almost identical average value within the error and only marginally greater dispersion.

We also confirm the lack of both *metal poor* and *super metal rich* M giants. This was originally noted in the Rich & Origlia (2005) Baade’s Window M giant distribution, but now

Table 1. Stellar parameters and abundances for our sample of giant stars in the inner Bulge field at $(l, b) = (0, -1)$.

#	RA	Dec	$(J - K)_0^a$	T_{eff}	$\log g$	v_r^b	[Fe/H]	[O/Fe]	[Si/Fe]	[Mg/Fe]	[Ca/Fe]	[Ti/Fe]	[C/Fe]	$^{12}\text{C}/^{13}\text{C}$
1	17:49:53.6	-29:31:22.4	0.85	4000	1.0	-327	+0.02 ± 0.11	+0.28 ± 0.16	+0.28 ± 0.20	+0.30 ± 0.16	+0.28 ± 0.19	+0.38 ± 0.20	-0.32 ± 0.17	
2	17:49:43.2	-29:18:50.9	1.25	3400	0.5	-66	-0.40 ± 0.08	+0.41 ± 0.11	+0.30 ± 0.21	+0.32 ± 0.09	+0.30 ± 0.12	+0.23 ± 0.14	-0.40 ± 0.11	
3	17:49:53.6	-29:30:41.2	1.04	3600	0.5	-76	-0.23 ± 0.08	+0.22 ± 0.11	+0.33 ± 0.17	+0.32 ± 0.08	+0.33 ± 0.12	+0.33 ± 0.14	-0.22 ± 0.10	
4	17:49:46.5	-29:19:17.8	1.37	3200	0.5	-7	-0.11 ± 0.07	+0.32 ± 0.11	+0.21 ± 0.16	+0.30 ± 0.08	+0.31 ± 0.12	+0.22 ± 0.13	-0.29 ± 0.10	
5	17:49:51.2	-29:31:00.4	1.21	3400	0.5	-192	-0.20 ± 0.08	+0.22 ± 0.12	+0.25 ± 0.17	+0.24 ± 0.09	+0.30 ± 0.12	+0.18 ± 0.15	-0.25 ± 0.11	
6	17:49:36.7	-29:18:53.8	1.40	3200	0.5	-32	-0.40 ± 0.08	+0.27 ± 0.11	+0.24 ± 0.14	+0.27 ± 0.09	+0.30 ± 0.12	+0.25 ± 0.14	-0.30 ± 0.11	
7	17:49:40.8	-29:18:17.2	1.09	3600	0.5	+45	-0.24 ± 0.03	+0.30 ± 0.05	+0.34 ± 0.13	+0.34 ± 0.04	+0.34 ± 0.05	+0.34 ± 0.07	-0.26 ± 0.08	
8	17:49:53.3	-29:30:28.02	1.10	3600	0.5	-1	-0.17 ± 0.03	+0.26 ± 0.05	+0.27 ± 0.13	+0.29 ± 0.04	+0.27 ± 0.05	+0.35 ± 0.07	-0.33 ± 0.08	
9	17:49:47.0	-29:18:49.2	1.47	3200	0.5	-15	-0.10 ± 0.04	+0.27 ± 0.06	+0.22 ± 0.13	+0.29 ± 0.04	+0.30 ± 0.06	+0.23 ± 0.07	-0.30 ± 0.08	
10	17:49:47.6	-29:18:59.8	1.42	3200	0.5	+121	-0.17 ± 0.04	+0.19 ± 0.06	+0.22 ± 0.13	+0.26 ± 0.04	+0.27 ± 0.06	+0.27 ± 0.07	-0.23 ± 0.08	
11	17:49:35.5	-29:18:46.1	1.49	3200	0.5	-168	-0.07 ± 0.04	+0.15 ± 0.06	+0.17 ± 0.13	+0.24 ± 0.04	+0.27 ± 0.06	+0.22 ± 0.07	-0.33 ± 0.08	
12	17:49:41.8	-29:18:25.4	1.36	3200	0.5	-94	-0.10 ± 0.09	+0.16 ± 0.14	+0.20 ± 0.17	+0.29 ± 0.10	+0.30 ± 0.13	+0.30 ± 0.15	-0.25 ± 0.11	
13	17:49:39.5	-29:20:12.3	1.00	3800	0.5	+165	-0.34 ± 0.09	+0.43 ± 0.10	+0.44 ± 0.21	+0.41 ± 0.10	+0.34 ± 0.13	+0.40 ± 0.14	-0.26 ± 0.12	
14	17:49:49.0	-29:19:50.8	1.07	3400	0.5	-181	-0.11 ± 0.07	+0.27 ± 0.11	+0.26 ± 0.19	+0.27 ± 0.08	+0.31 ± 0.12	+0.19 ± 0.15	-0.29 ± 0.10	
15	17:49:39.4	-29:20:21.3	1.33	3400	0.5	-34	-0.42 ± 0.08	0.37 ± 0.11	0.32 ± 0.15	0.32 ± 0.09	0.32 ± 0.12	0.26 ± 0.14	-0.38 ± 0.11	
16	17:49:40.7	-29:20:13.3	1.35	3600	0.5	-90	-0.46 ± 0.08	0.37 ± 0.10	0.36 ± 0.15	0.34 ± 0.09	0.36 ± 0.12	0.36 ± 0.14	-0.24 ± 0.11	
17	17:49:35.4	-29:17:45.0	1.25	3400	0.5	-206	-0.25 ± 0.08	+0.22 ± 0.11	+0.19 ± 0.17	+0.23 ± 0.09	+0.25 ± 0.12	+0.25 ± 0.14	-0.35 ± 0.10	

^aThe (J–K) colors are from 2MASS and have been corrected for reddening using $E(B-V)=2.9$.

^bHeliocentric radial velocity in km s^{-1} .

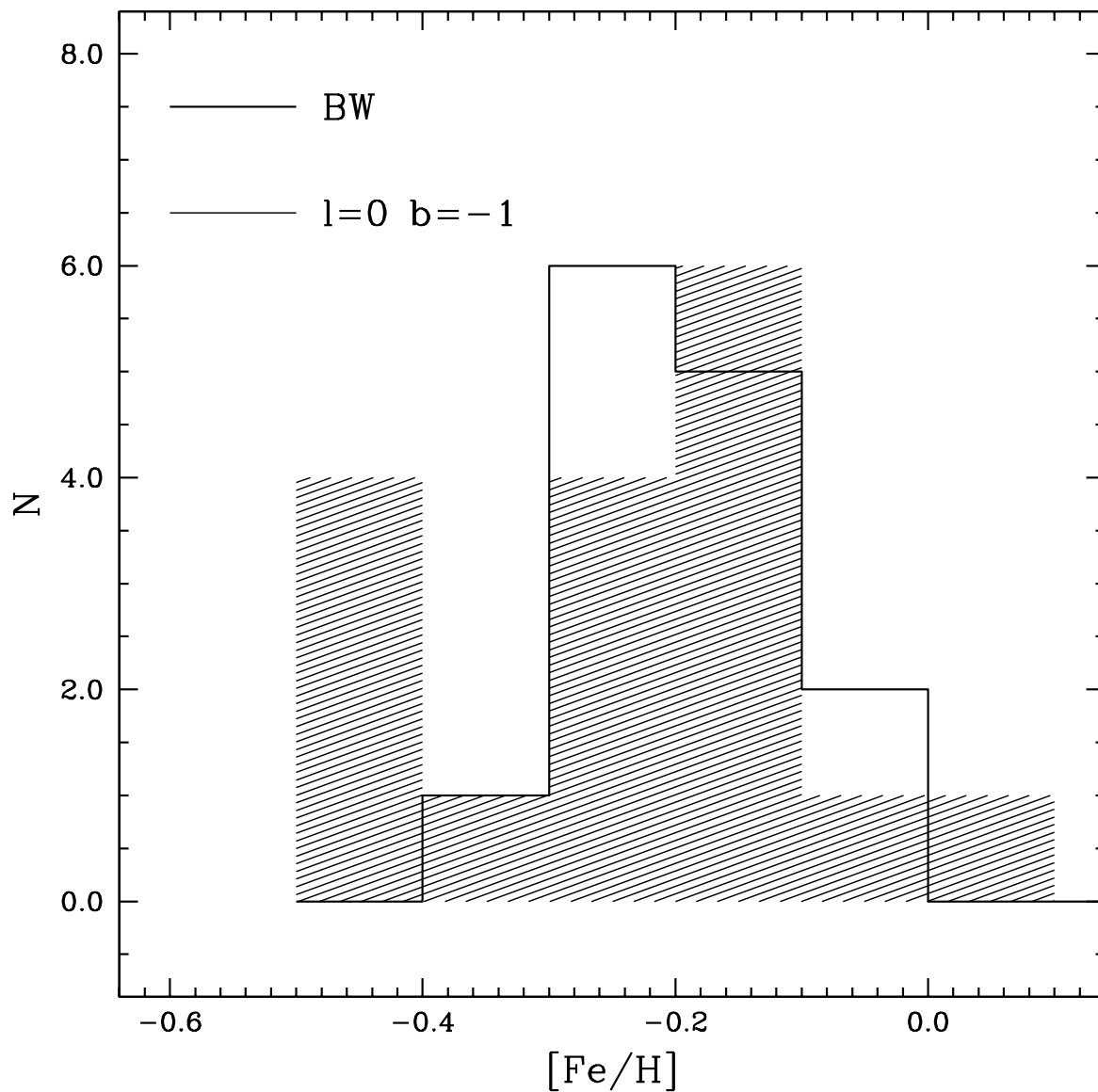


Fig. 2.— Histogram of the metallicity distribution in $[\text{Fe}/\text{H}]$, for the observed giants in the inner bulge field at $(l, b) = (0^\circ, -1^\circ)$ (shaded histogram) and in Baade's window $(l, b) = (0.9^\circ, -4^\circ)$ (solid line, Rich & Origlia (2005)), for comparison. Notice that there is no significant difference between the two fields.

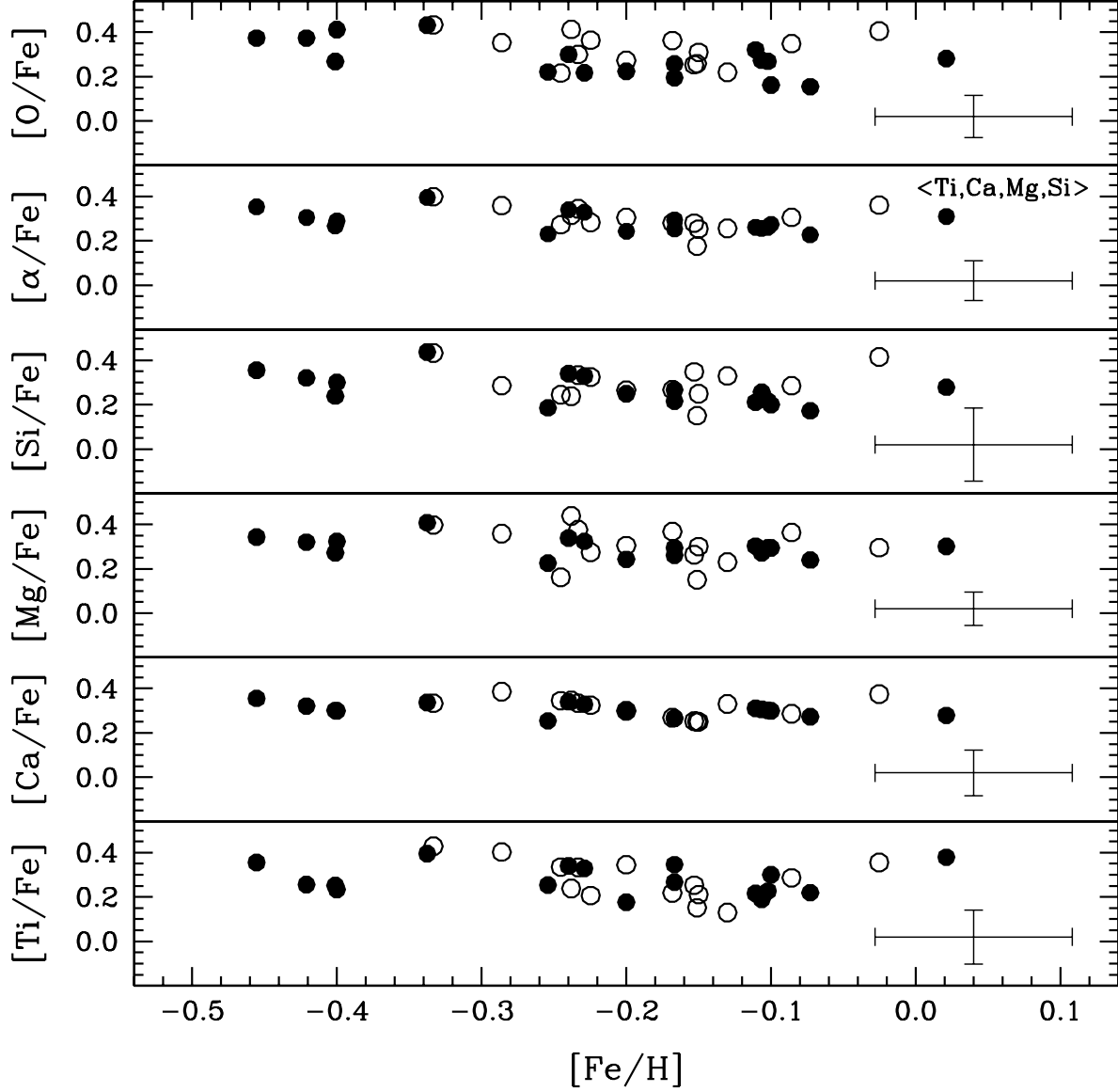


Fig. 3.— α/Fe as a function of $[Fe/H]$ for the observed giants in the inner bulge field at $(l, b) = (0^\circ, -1^\circ)$ (filled circles) and in Baade’s window (open circles, Rich & Origlia (2005)), for comparison. Typical errors are plotted in the bottom-right corner of each panel. There is no evidence for a gradient in $[\alpha/Fe]$ in the bulge.

persists in a sample that, in total, is nearly three times as large. We know that the metal poor end will be poorly represented, as few stars with $[\text{Fe}/\text{H}] < -1$ will evolve to be cool enough to develop TiO bands and become M giants at the RGB tip. However, the lack of *super metal rich* M giants is a concern. Indeed, although they represent only a fraction ($\leq 20\%$, Fulbright, McWilliam & Rich (2006)) of the bulge population, they are definitely present in all bulge K giant studies. We speculate that their low intrinsic numbers and rapid evolution may make their detection statistically unlikely. Moreover, the possible enhanced mass loss at super solar metallicities (see e.g. Castellani & Castellani 1993) may also prevent the most metal rich stars from reaching the RGB tip. It is important to explore these issues with a larger sample, but the total of 31 M giants observed in these two fields is now large enough that the lack of stars with $[\text{Fe}/\text{H}] > 0.1$ is a significant concern.

Our survey shows a rather homogeneous α -enhancement by $\approx +0.3 \pm 0.1$ dex up to solar metallicity, without significant differences among the various α -elements (see Fig. 3), and similar to measurements in the Baade’s window. Such an enhancement of the $[\alpha/\text{Fe}]$ abundance ratio suggests that at the epoch of the bulge formation, mainly type II SNe were contributing to the enrichment of the interstellar medium. It also indicates that the overall formation process should have ended before the bulk of type Ia SNe have exploded, i.e. well within a few Gyr, the precise timescale depending on the SN modeling (see e.g. Greggio 2007).

We have also derived carbon abundances for all of the observed stars from analysis of the CO bandheads. We find some degree of $[\text{C}/\text{Fe}]$ depletion ($< [\text{C}/\text{Fe}] > = -0.29 \pm 0.02$) with respect to solar values and very low $^{12}\text{C}/^{13}\text{C}$ ($< ^{12}\text{C}/^{13}\text{C} > = 6.5 \pm 0.3$), as also measured in Baade’s window M giants, confirming the presence of extra-mixing processes during the RGB phase of evolution in metal-rich environments.

From our detailed analysis of chemical abundances and abundance patterns we can thus exclude any major abundance gradient in the inner bulge.

Finally, we have also measured radial velocities and velocity dispersion for the observed stars, as for the Baade’s window giants. The overall velocity dispersion of the global sample of 31 M giants turns out to be $\sigma_{\text{vr}} \approx 116 \pm 15$ km/s, fully consistent with bulge kinematics.

Theory concerning the formation of spheroids has evolved, beginning with Eggen et al. (1962), who proposed violent relaxation and dissipative collapse. In the CDM scenario, spheroids would form from the mergers of disks. Further, large galaxy surveys now suggest that the spheroid-dominated ”red sequence” has grown in mass since $z \approx 1$ (Bell et al. 2004), implying that some spheroids have come into existence relatively later than the age of the Galactic bulge population. A widely supported scenario for bulge formation was initially

proposed by Raha et al. (1991). In this scenario, a massive disk develops bending modes that ultimately thicken the disk vertically, producing a peanut-shaped bar. These ideas have been developed by many other theoretical studies e.g. Pfenniger & Norman (1990). The bar thickening hypothesis predicts that no vertical abundance gradient should be present. Carefully weighing the existing evidence, Kormendy & Kennicutt (2004) conclude that the Galactic bulge has likely been formed via secular processes, but they are perplexed by the strong evidence for its age being similar to that of the halo. The recent survey of bulge kinematics by Rich et al. (2007) supports the idea that the bulge is kinematically distinct from the inner disk and that while the deprojection of the bulge demands some elongated structure (Zhao 1996), the new velocity field also requires the presence of retrograde orbits by construction. While the lack of an abundance gradient is consistent with secular evolution models, the great age of the bulge/bar remains as a problem for this picture.

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REFERENCES

- Ballero, S. K., Matteucci, F., Origlia, L., & Rich, R. M. 2007, *A&A*, 467, 123
- Bell, E. F., et al. 2004, *ApJ*, 608, 752
- Castellani, M., & Castellani, V. 1993, *ApJ*, 407, 649
- Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, *ApJ*, 136, 748
- Greggio, L. 2007, *A&A*, in press (astro-ph/0504376v2)
- Grevesse, N., & Sauval, A. J. 1998, *Space Science Reviews*, 85, 161
- Figer, D. F., Rich, R. M., Kim, S. S., Morris, M., & Serabyn, E. 2004, *ApJ*, 601, 319
- Frogel, J. A., Tiede, G. P., & Kuchinski, L. E. 1999, *AJ*, 117, 2296
- Fulbright, J. P., McWilliam, A., & Rich, R. M. 2006, *ApJ*, 636, 821

- Fulbright, J. P., McWilliam, A., & Rich, R. M. 2007, *ApJ*, in press (astro-ph/0609087)
- Kormendy, J., & Kennicutt, R. C., Jr. 2004, *ARA&A*, 42, 603
- Kuijken, K., & Rich, R. M. 2002, *AJ*, 124, 2054
- Matteucci, F., Romano, D., & Molaro, P. 1999, *A&A*, 341, 458
- McLean, I. et al. 1998, *SPIE*, 3354, 566
- McWilliam, A., & Rich, R.M. 1994, *ApJS*, 91, 749
- Montegriffo, P., Ferraro, F.R., Fusi Pecci, F., & Origlia, L., 1998, *MNRAS*, 297, 872
- Origlia, L., Moorwood, A. F. M., & Oliva, E. 1993, *A&A*, 280, 536
- Origlia, L., Ferraro, F. R., Fusi Pecci, F., & Oliva, E. 1997, *A&A*, 321, 859
- Origlia, L., Rich, R. M., & Castro, S. 2002, *AJ*, 123, 1559
- Origlia, L., Ferraro, F. R., Bellazzini, M., & Pancino, E. 2003, *ApJ*, 591, 916
- Origlia, L., & Rich, R. M. 2004, *AJ*, 127, 3422
- Ortolani, S., Renzini, A., Gilmozzi, R., Marconi, G., Barbuy, B., Bica, E., & Rich, R. M. 1995, *Nature*, 377, 701
- Pfenniger, D., & Norman, C. 1990, *ApJ*, 363, 391
- Raha, N., Sellwood, J. A., James, R. A., & Kahn, F. D. 1991, *Nature*, 352, 411
- Ramírez, S. V., Stephens, A. W., Frogel, J. A., & DePoy, D. L. 2000, *AJ*, 120, 833
- Rich, R.M., & Origlia, L. 2005, *ApJ*, 634, 1293
- Rich, R. M., Reitzel, D. B., Howard, C. D., & Zhao, H. 2007, *ApJ*, 658, L29
- Schultheis, M. et al. 1999, *A&A*, 349, 69
- Vieira, K., Dinescu, D., van Altena, W., Girard, T., & Méndez, R. A. 2006, *Rev. Mex. A&A*, 25, 35
- Zhao, H. S. 1996, *MNRAS*, 283, 149
- Zoccali, M., et al. 2003, *A&A*, 399, 931
- Zoccali, M., et al. 2006, *A&A*, 457, 1

